FINAL REPORT
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Title: **"A Study of Nonthermal X-Ray and Radio Emission from the O Star 9 Sgr"**

PI: **Dr. Wayne L. Waldron, Space Applications Corporation**

CoIs: **Drs. Michael F. Corcoran and Stephen A. Drake (GSFC/USRA)**

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ABSTRACT

The observed X-ray and highly variable nonthermal radio emission from OB stars has eluded explanation for more than 18 years. The most favorable model of X-ray production in these stars (shocks) predicts both nonthermal radio and X-ray emission. The nonthermal X-ray emission should occur above 2 keV and the variability of this X-ray component should also be comparable to the observed radio variability. To test this scenario, we proposed an ASCA/VLA monitoring program to observe the OB star, 9 Sgr, a well known nonthermal, variable radio source and a strong X-ray source. We requested 6 25 ks ASCA observations with a temporal spacing of approximately 4 days which corresponds to the time required for a density disturbance to propagate to the 6 cm radio free-free photosphere. The X-ray observations were coordinated with 5 multi-wavelength VLA observations. These observations represent the first systematic attempt to investigate the relationship between the X-ray and radio emission in OB stars.

Key words: **X-rays: stars -- radio continuum: stars -- stars: early-type -- stars: individual (9 Sgr) — stars: winds — stars: mass loss**

1. INTRODUCTION

For more than 18 years, the observed X-ray and nonthermal radio emission from OB stars has eluded explanation. Coronal regions were proposed before the discovery of X-ray emission from OB stars (Cassinelli & Olson 1979) and detailed coronal modeling of X-ray emission was carried out by Waldron (1984). Many different shock models, as first suggested by Lucy & White (1980), have also been proposed. Based on several theoretical and numerical explorations of the line force instability mechanism (e.g., Owocki et al. 1988; and references therein), the general consensus among most researchers is that this mechanism produces a distribution of shocks in a stellar wind which in turn is responsible for the observed X-ray emission. A shock distribution also provides a natural mechanism to produce nonthermal radio emission as shown by White (1985) and Biermann & Cassinelli (1993). These strong shocks, by way of Fermi acceleration, produce a small population of relativistic electrons which are carried by the wind to regions beyond the radio free-free photosphere, where they produce observable synchrotron emission. Nonthermal radio emission is present in at least 25% of the detected OB radio sources (Bieging et al. 1989). As shown by Chen & White (1991), this mechanism also predicts that nonthermal X-ray emission should clearly be observable beyond ~ 2 keV, which they claim is present in the SSS spectra of three Orion OB supergiants.

Waldron et al. (1998), using all archived X-ray and radio data, investigated the long term relationship between X-ray and radio emission of the highly variable, nonthermal radio OB stars in the Cyg OB2 association. They found that over a period of approximately 15 years, the radio emission was highly variable (by as much as a factor of 10), and displayed both thermal and nonthermal characteristics. On the other hand, the observed X-ray emission over this period was essentially constant. It is intriguing that every time the radio is observed, it is different, but the X-ray emission remains constant. It seems implausible that we just "happen to miss" the X-ray variability if the wind is as variable as suggested by the radio emission. One possible explanation is that the previous X-ray instruments were not sensitive enough to hard X-rays (> 2 keV). It is important to point out that the available X-ray and radio data were taken at random times. Although the results of Waldron et al. (1998) are interesting, a conclusion about the relationship between the X-ray and radio emission cannot be made. Since the shock model is widely accepted as the source of the OB X-ray emission, it is extremely important to test the shock model predictions regarding nonthermal X-ray and radio emission. The basic parameter that determines the strength of the hard X-ray emission is the stellar wind mass loss rate.

ASCA observations have detected excess hard X-ray emission above 2 keV in several OB stars; λ Ori (O8III) (Corcoran et al. 1994); ζ Ori (O9.7Ib) and ζ Oph (O9.5V) (Waldron et al. 1997), and; τ Sco (B0V) (Cohen et al. 1997). However, none of these stars are nonthermal radio sources, and except for ζ Ori, none of these stars have sufficient mass loss to produce the nonthermal hard X-ray emission. In addition, the S/N of these ASCA observations were not sufficient to allow us to determine if these hard components are thermal or nonthermal. On the other hand, the Cygnus OB2 association OB stars, which possess the largest mass loss rates and show highly variable nonthermal radio emission, show no evidence of any hard X-ray emission above 2 keV in their ASCA spectra (Kitamoto & Mukai 1996). However, the SIS image of this field shows high energy contamination from the strong, variable X-ray source, Cyg X-3 (~ ½ degree off-axis). Kitamoto & Mikai (1996) discussed the problems associated with this contamination. It is quite possible that if these stars have a hard component, it may have been lost in the high energy background subtraction. Regardless, there appears to be a direct contradiction of the Chen & White model based on current ASCA observations.

To clear up this apparent contradiction, we proposed ASCA and VLA observations of a well known variable nonthermal radio OB star, 9 Sgr (O4V), to monitor the X-ray and radio emission. This star was among the first detected nonthermal radio stars (Abbott et al. 1984). Over a 16 year time frame, 20 random VLA radio observations of 9 Sgr were obtained (see Table 2). It is also a strong X-ray source as evident by one IPC pointing (Cassinelli et al. 1981) and four PSPC pointings. The X-ray data are given in Table 1. The main advantage, evident from the IPC and PSPC images, is that it is relatively isolated, and an ASCA pointing centered on 9 Sgr should not be contaminated from any anomalous hard X-ray sources. There is extended soft X-ray emission below 0.4 keV, as discussed by Cassinelli et al. (1981), but should not be a factor in the ASCA energy range. In addition, the VLA radio maps clearly show that 9 Sgr is a radio point source.

To our knowledge, this represents the first attempt to carry out such a study. ASCA is ideal for this study for two reasons: (1) the large energy range (0.5-10 keV) which is needed to sample the thermal (soft) and nonthermal (hard) X-ray components, and; (2) the ability to resolve line emission so that we can determine if a hard component is thermal or nonthermal.

2. SCIENCE OBJECTIVES

2.1. Observing Strategy

We proposed to monitor the X-ray emission from 9 Sgr over a period of 24 days at 4 day intervals, yielding 6 ASCA pointings of 25 ks each for a total exposure time of 150 ks. The justification for these time scales are discussed below. In addition, we proposed 6 VLA observations of 9 Sgr within a day of the ASCA observations, along with one VLA observation one week prior to the start of the X-ray monitoring program and another one week after. The VLA observations will be multiple wavelength observations at 2, 3.6, 6, and 20 cm. From the ASCA GO VIEWING program, the best time critical window for 9 Sgr is 6Mar97 to 12Apr97, which is consistent with the VLA window. Although 9 Sgr is not suspected to have a binary component (Garmany et al. 1980; Bieging et al. 1989), to test for the possibility of a very close binary companion (as appears to be the case in nonthermal radio Wolf-Rayet sources, e.g., van der Hucht et al. 1992), we will coordinate a VLBA observation with one of our VLA observations to obtain milli-arcsecond spatial resolution.

There are three basic time scales associated with wind structures in OB stars; (1) wind travel time to the radio emission region; (2) stellar rotation rate, and; (3) wind travel time in the accelerating wind region. The first, and most important to the proposed effort, is the wind travel time required for a density disturbance to propagate to the radio photosphere (radio optical depth ~ 1) For 9 Sgr, this occurs in the range from 40 (2 cm) to 200 (20 cm) stellar radii dependent on the radio wavelength (e.g., the time required to travel to the 20 cm region is ~ 4.9 times longer than the time required to travel to the 2 cm region). For the adopted stellar parameters, the wind travel times in days are, 1.8 (2 cm), 2.8 (3.6 cm), 3.9 (6 cm), and 9.1 (20 cm). The next important time scale is the stellar rotation period. 9 Sgr has an observed vsini ~ 150 km s^{-1}, and a stellar radius = 16 solar radii, yielding a plausible range in rotation period of 3.8 to 5.4 days. The last is the time scale associated with the accelerating region of the wind (between ~ 1.2 to 5 stellar radii) which is typically ~ 8 hours.

By selecting a time interval of 4 days covering 24 days, we will be sampling 6 travel times to the 6 cm region, 2.5 travel times to the 20 cm region, and multiple travel times to the other radio wavelength regions. This 4 day interval will also allow us to sample 4-6 rotation periods. Furthermore, the 25 ks per ASCA pointing will allow us to investigate hourly variability of the X-rays in the accelerating region.

2.2. Model Predictions

The main objective of this proposal is to establish whether a systematic relationship exists between the X-ray and nonthermal radio emission. From the White (1985) model for nonthermal radio emission and the Chen & White (1991) model for nonthermal X-ray emission, we can derive a relation showing the dependence of X-ray emission on nonthermal radio emission, assuming that the underlying driver is a variable wind density (i.e., mass loss rate, which in turn also effects the thermal X-ray source due to its wind emission measure and wind attenuation). Figure 1 illustrates the expected percent change in the SIS0 count rate for both the total and the 2-7 keV energy bands as a function of the percent change in nonthermal radio emission. The large change in the SIS0 hard band emission is due to the fact that the hard band varies as the square of mass loss and the nonthermal radio emission varies linearly with mass loss. Although the total SIS0 band emission is also proportional to the square of the mass loss, since the lower energies are subjected to stellar wind absorption (which is linearly proportional to mass loss), the total band variability is smaller and comparable to the nonthermal radio variability. Therefore, since the radio is highly variable as evident in Figure 3b, our ASCA observations should clearly reflect larger or similar variability if the shock scenario is correct.

3. OBSERVATIONS

3.1. X-ray Observations

We were only granted two 25 ks ASCA observations of 9 Sgr, and actual exposure times were reduced by 24% and 41% respectively. As a further complication, we found that our SIS images of 9 Sgr were contaminated by a strong supernova remnant X-ray source located ~ 1 degree off-axis. Although similar to the contamination reported by Kitamoto & Mukai (1996) for the Cyg OB2 association, the 9 Sgr contamination was more severe. Various background subtraction techniques were tested, and averaged, to obtain the best representative SIS X-ray spectra for 9 Sgr (see Figs. 2c & 2d). In addition, the resultant ASCA SIS0 count rates were found to be ~ 2.2 times smaller than expected. Based on PSPC spectra, we were expecting SIS0 count rates of ~ 0.089. Due to the uncertainty in the background contamination and the lower than expected emission level, the spectral quality limits our ability to carry out detailed spectral analyzes.

Table 1 lists all X-ray observations of 9 Sgr. The columns provide information on X-ray instrument, observation date, X-ray image number, exposure time, X-ray count rate, signal-to-noise (S/N), and observed X-ray flux (integrated between 0.2 - 5 keV). The X-ray fluxes were obtained from best fits to the data (see discussion in Sec. 4). The IPC data was obtained from Cassinelli et al. (1981). The ROSAT All-Sky Survey (RASS) data was obtained from Berghofer et al. (1996), and the other PSPC data were obtained from the HEASARC archive using the standard FTOOL routines to extract spectra.

3.2. Radio Observations

We were granted 5 multi-wavelength (2, 3.6, 6, & 20 cm) VLA observations of 9 Sgr. We were not granted VLBA time so we could not search for a close binary component. The VLA observations started 2 days after the last ASCA observation and subsequent observations were incremented at ~ 3 to 4 days. We had hoped that our monitoring program would occur when the VLA was in the A or B configuration (Mar97). Unfortunately our program was scheduled when the VLA was in the D configuration. In this configuration the large H II region (M8) which is ~ 3 arc minutes from 9 Sgr, contaminated the radio emission from 9 Sgr (this would not have happened in either A or B configurations). Various VLA radio source extraction procedures were attempted to no avail. As a result, we were only able to obtain one firm radio detection at 3.6 cm, and 4 reasonable upper limit at 3.6 cm, and one at 2 cm. The remaining observations produced very large and uninteresting upper limits (indicated in Table 2 by "???").

Table 2 list all VLA radio observations from 9 Sgr. The data prior to 1990 are from Beiging et al. (1989). The data during Jan93 to Feb93 are from Beasley (1998). The data from Jun92 is from one of our VLA observing runs. The radio variability is clearly present in the data. The best time sampling of a wind flow time (~ 4 days) was obtained by Beasley (1998) which shows highly variable radio emission at both 3.6 and 6 cm. Unfortunately no X-ray observations were taken during this time frame. It is also clear from the multi-wavelength observations that the resultant spectral indices are < 0 indicating a flat or rising nonthermal radio spectrum. Although our VLA data obtained in Oct97 are not very interesting, the 3.6 cm detection and upper limits are consistent with the previous 3.6 cm data.

4. RESULTS

Due to unexpected contamination in both the X-ray and radio data, our primary objective of obtaining the first systematic study of X-ray and radio variability could not be achieved. The contamination in the X-ray data also limits our ability to establish the presence of a high energy (> 2 keV) nonthermal component. Hence, this report will focus on the long-term X-ray variability and comparisons between the PSPC and SIS0 best fit X-ray parameters.

4.1. Spectral Fits

Using the basic stellar wind X-ray absorption model developed by Waldron (1984), and the MEKAL emissivity model (using solar abundances), we obtained spectral fits to the PSPC spectra (the RASS PSPC data have too few counts) and the two SIS0 spectra. Assuming a fixed ISM column density of 2.1×10^{21} cm^{-2}, the best fit parameters, X-ray temperature (T_X), emission measure (EM_X), stellar wind column density (N_W), and intrinsic (corrected) and observed (uncorrected) X-ray flux (0.2-5 keV) are given in Table 3 (the last column provides the ratio of the chi-square to the degrees-of-freedom. The data were rebind to obtain a minimum of 10 counts per bin. The 99% confidence region suggest errors in our fitting parameters ranging from 10% to 20%. The PSPC fits are shown in Figures 2a & 2b, and the SIS0 fits are shown in Figures 2c & 2d.

The most obvious result from our fits is that between Oct92 and Oct97, EM_X, N_W, and X-ray flux have steadily decreased, while T_X remained essentially constant. The predicted values of N_W and T_X indicate that the X-rays originate from within the stellar wind, supportive of the shock scenario. The change in N_W and EM_X suggests that either the wind density changed due to a change in mass loss rate (required by the nonthermal radio models to explain the high degree of variability), or a drastic change in the shock location occurred (which would not affect the radio emission). If the shock location is changing, then one would also expect T_X to change, which is not observed at any significant level. Hence, we can surmise that the observed X-ray variability maybe due to a changing mass loss rate, which would also be consistent with the observed radio variability.

4.2. Long-Term Variability

Over an 18 year time span random X-ray and radio observations of the O4V star, 9 Sgr, have been obtained. Figure 3 shows the time history of the observed X-ray flux (Fig. 3a) and the 3.6 and 6 cm radio emission (Fig. 3b). Since 9 Sgr is a nonthermal radio source, it is not surprising that it is highly variable. However, the apparent long-term variability seen in the X-ray emission has not been noted in any previous studies. It is generally accepted that the X-ray emission from OB stars is relatively constant (Berghofer & Schmitt 1995), and any X-ray variability is believed to be $< \pm 20\%$. Although shock models predict that the X-ray and nonthermal radio variability should be correlated, previous studies of OB nonthermal radio sources showed no evidence of X-ray variability (Waldron et al. 1998). Unfortunately, due to the limited sampling of X-ray data, we cannot determine whether the X-ray and radio variability are correlated. If our proposed monitoring program had been successful, we may have been able to resolve this issue. Clearly this star represents one of the best candidates to carry out a detailed X-ray/radio monitoring program.

4.3. Evidence for Nonthermal Component?

If the shock scenario is indeed responsible for the observed nonthermal radio emission, ASCA should clearly resolve a nonthermal X-ray component above 2 keV. Using the stellar parameters adopted by White (1985) (of which the two key parameters are mass loss rate = 4×10^{-6} M⊙ yr^{-1} and terminal velocity = 2950 km s^{-1}), and the nonthermal X-ray model of Chen & White (1991), which predicts a power law with an energy spectral index of 0.5, the expected SIS0 count rate above 2 keV should be ~ 0.013. Our SIS0 spectral distributions (Figs. 3c & 3d) hint that a hard X-ray emission excess may be present above 2 keV, yielding count rates above 2 keV of 0.0018±0.0014 (24Sep97) and 0.0048±0.0013 (1Oct97), significantly lower than expected. However, due to the contamination by the nearby strong X-ray source, we are not able to make any conclusive statement about the existence and strength of this hard X-ray component.

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TABLE 1. History of 9 Sgr X-ray Observations

Instr	Date	Image #	Exp. Time ks	count rate cnt s^{-1}	S/N	obs $F_X/10^{-12}$ erg cm^{-2} s^{-1}
IPC[a]	11Sep79	3124	3.90	0.057±0.005	15.3	1.10±0.15
PSPC	RASS[b]	----	0.30	0.134±0.026	5.2	1.35±0.26
PSPC	17Mar91	200194n00	1.64	0.177±0.011	16.6	1.79±0.11
PSPC	4Oct92	201261n00	4.50	0.176±0.006	27.6	1.78±0.06
PSPC	1Apr93	900374n00	10.43	0.164±0.004	40.7	1.62±0.04
SIS0	24Sep97	25016000	18.60	0.041±0.003	16.1	1.37±0.10
SIS0	1Oct97	25016010	14.85	0.038±0.002	19.3	1.45±0.10

[a] Data from Cassinelli et al. (1981).

[b] For the ROSAT All-Sky Survey (RASS) data, a specific date and image number are not available. The RASS lasted approximately 6 months after launch (Jun90).

TABLE 2. History of VLA Data Obtained for 9 Sgr

Date	Radio Flux (mJy)			
	2 cm	3.6 cm	6 cm	20 cm
13Jul79			1.00±0.40	
22May80			1.80±0.30	
9Feb82	< 2.4		2.50±0.30	
26May82			2.40±0.30	3.60±0.30
22Aug83	< 0.8		1.50±0.20	3.90±0.40
20Sep83			1.60±0.20	
27Nov84			2.00±0.20	
28Jan85			1.50±0.10	
16Feb85	0.70±0.10		1.90±0.10	
24Jun92		2.20±0.30		
21Jan93		1.48±0.06	2.25±0.07	
24Jan93		1.61±0.05	2.10±0.07	
29Jan93		1.37±0.07	2.15±0.13	
1Feb93		1.19±0.08	1.77±0.13	
14Feb93		1.36±0.12	2.38±0.13	
3Oct97	< 1.1	< 1.6	???	???
7Oct97	???	< 1.8	???	???
11Oct97	???	< 1.7	???	???
15Oct97	???	< 1.3	???	???
18Oct97	???	1.30±0.30	???	???

The "???" entries indicate that although data were obtained at these wavelengths, the radio contamination limited our ability to extract meaningful upper limits.

TABLE 3. Best Fit X-ray Parameters for PSPC and SIS0 Spectra of 9 Sgr

Instr	Date	$T_X/10^6$ K	$EM_X/10^{56}$ cm^{-3}	$N_W/10^{21}$ cm^{-2}	flux (10^{-12} erg cm^{-2} s^{-1}) intrinsic	observed	χ^2/DOF
PSPC	17Mar91	3.24	14.69	10.26	55.70	1.79	9.3/12
PSPC	10Apr92	2.86	6.32	4.95	23.63	1.78	11.9/15
PSPC	1Apr93	3.24	4.12	4.28	15.61	1.62	26.0/18
SIS0	24Sep97	3.66	5.73	7.66	22.29	1.37	26.6/30
SIS0	1Oct97	3.66	7.55	8.85	29.34	1.45	32.3/32

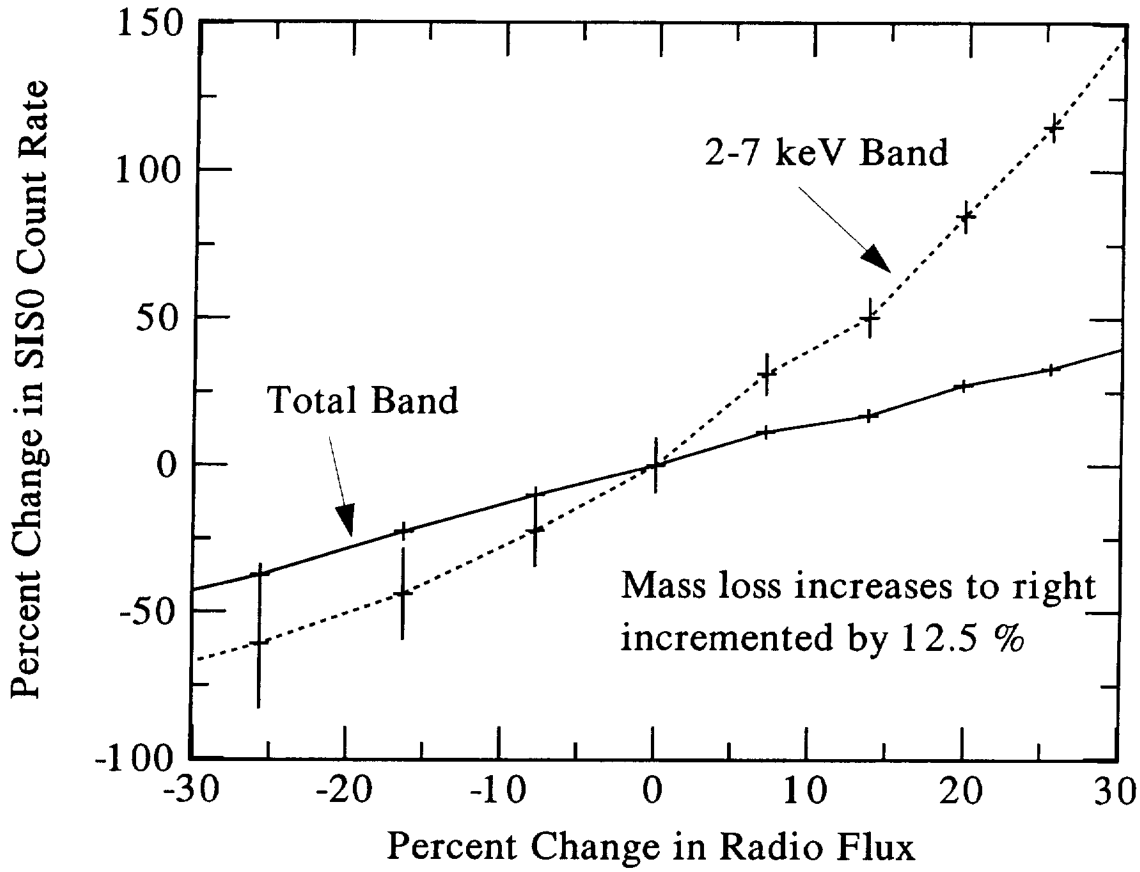

Figure 1 The predicted percent change in SIS0 count rates for the total and 2-7 keV energy bands as a function of the percent change in nonthermal radio flux. In this simulation the variable parameter is the stellar wind mass loss rate. The error bars are based on a 25 ks exposure. This predicts that the nonthermal X-ray variability will be significantly stronger than the nonthermal radio variability. In addition, the total SIS0 count rate variability will be comparable to the variable nonthermal radio emission.

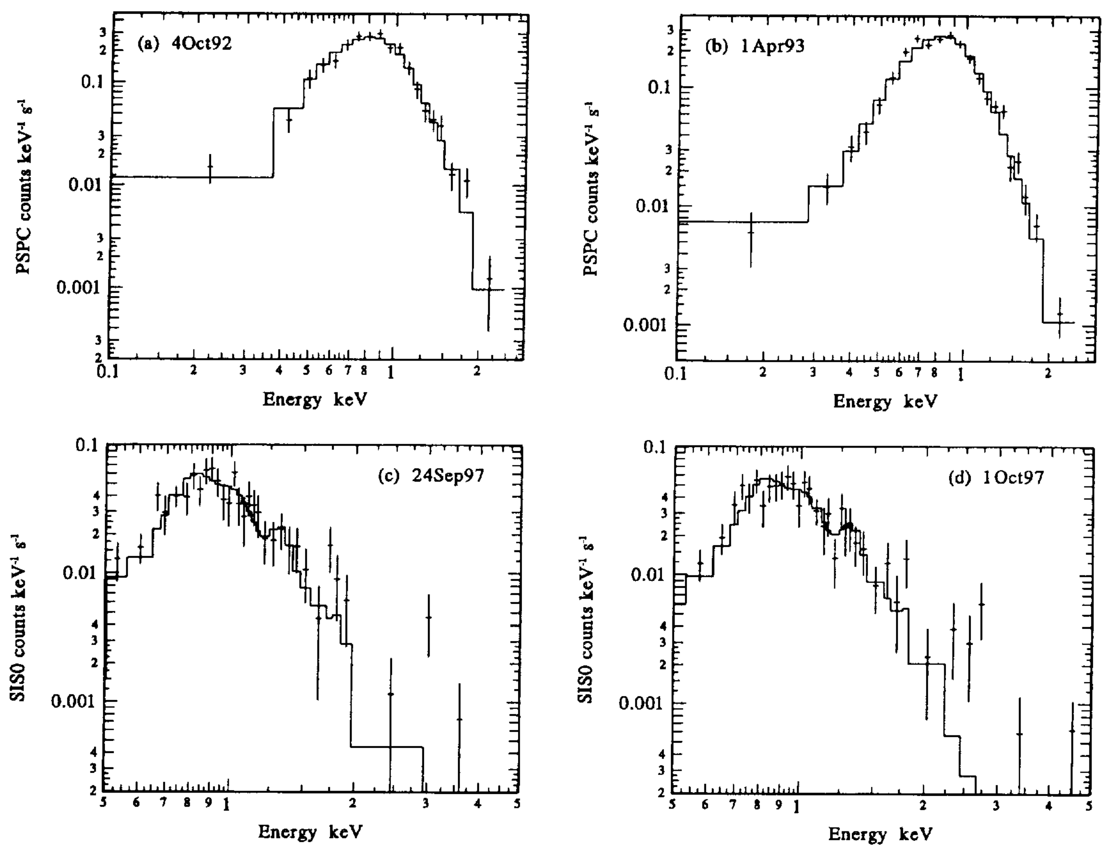

Figure 2 Comparisons of the observed PSPC and SIS0 spectral distributions with the stellar wind absorption model predictions. Only the two highest S/N PSPC observations are shown. The best fir parameters are given in Table 3. All data have been rebind to have at least 10 counts per bin. The SIS0 data suggest that there may be an additional high energy emission component above 2 keV which may be real or an artifact of the background subtraction uncertainty.

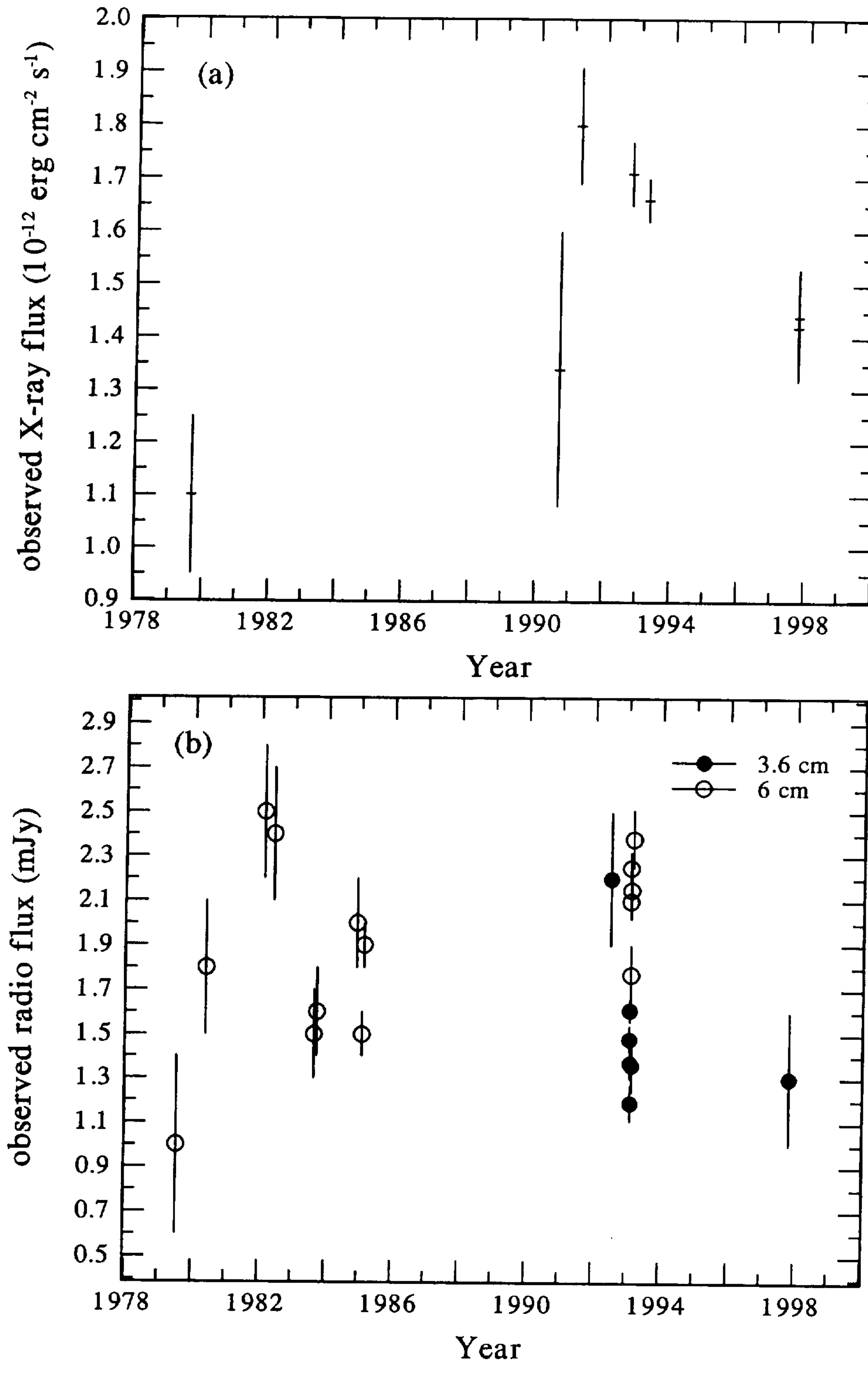

Figure 3 Chronological behavior of the observed X-ray (a) and radio (b) emission from the O4V star, 9 Sgr. As shown in Fig. 3b, the highly variable nature of the radio emission, represented by the 3.6 and 6 cm data, is clearly evident. The X-ray data also suggests that significant long-term X-ray variability is also present. The limited data sample does not allow us to establish whether the X-ray and radio variability are correlated.

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Cols: Drs. Michael F. Corcoran and Stephen A. Drake

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Space Applications Corporation
9315 Largo Drive West, Suite 250
Largo, MD 20774

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14. SUBJECT TERMS
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